

Life Cycle Assessment of Power-to-Liquid for Aviation: A Case Study of a Passenger Aircraft

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Abstract. The aviation sector is estimated to require a widespread deployment of sustainable fuels next to developments in aircraft technology and improvements in operations and infrastructure to efficiently reduce its climate impact. A possible pathway for more sustainable aviation fuels could be fuel production using hydrogen via water electrolysis with renewable energy followed by Fischer-Tropsch synthesis, also known as Power-to-Liquid (PtL). In order to investigate whether this fuel pathway contributes to the reduction in environmental impacts, we conduct an environmental Life Cycle Assessment (LCA) compared to fossil fuel for the use in a narrow-body short- to medium-haul aircraft fleet. Within the LCA, the focus lies on the phases of fuel production and operation of the aircraft's life cycle. Unlike most LCA studies in aviation, the impacts of the flight emissions are computed based on the aircraft characteristics and considering the geographic position and altitude of the aircraft for a global route network. Since the aircraft design is not affected by the fuel types under investigation, the aircraft production and end-of-life phases are not considered in the LCA. This contribution shows the potential of PtL for aviation in a well-to-wake environmental sustainability analysis considering climate change and nine additional impact categories.

1 Introduction

Aviation is one of the sectors considered as hard-to-abate with respect to its climate impact. New solutions need to be found to reach the goals of the Paris Agreement of 2016. Power-to-Liquid (PtL) as aviation fuel is one possible pathway to reduce aviation's greenhouse gas emissions, especially for medium and longer distances, where electrification concepts, e.g. using batteries, are not expected to be applicable soon enough.

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Several studies have investigated alternative fuels for aviation and their environmental impacts over the last years. Some of them focus on the production of the alternative fuels and do not model the combustion during the operation phase of the aircraft [1, 2]. Others do also consider the impacts of emissions during flight and base the impact analysis on statistical data from emission databases and on average aircraft and flight characteristics; however, they do not consider PtL among the alternative fuels analysed [3, 4].

In this study, we close this gap by including both the fuel production phase for PtL and fossil jet fuel and the operation of an entire fleet of aircraft in the environmental impact analysis. Additionally, we consider the aircraft performance as well as the geographic position and altitude of the aircraft on a global fleet route network to determine the climate change impact of emissions during flight.

2 Method

2.1 Goal and scope

The methodology employed follows the main principles of an LCA as described in ISO 14040/44. The system chosen for this case study is a fleet of advanced short-to-medium range turbofan aircraft with entry into service in 2040. The aircraft is designed to fly a distance of 1500 nautical miles with 250 passengers on board at a cruise speed of Mach 0.78 using the methodology described in [5]. This type of aircraft represents a high share of the total flights and more than one-third of the CO₂ emissions from aviation [6].

The goal of the study was to compare the environmental impacts generated by the selected aircraft fleet using different fuels, namely fossil jet fuel and synthetic fuel following the PtL pathway. The analysis has a global scope and considers a typical lifetime of 30 years of such a fleet. The primary data generated by inhouse methods of the German Aerospace Center are combined with background data from the ecoinvent database (version 3.7.1) and secondary data from scientific literature. Finally, the ILCD method and the open source software Brightway2 are used to conduct the LCA. The functional unit is 1 passenger kilometre.

The system boundaries of the analysis include the production of the hydrocarbon fuel – either fossil or synthetic – and the fleet operation. It is assumed that the aircraft itself does not change depending on whether fossil or synthetic fuel is used. Thus, the lifecycle phases of manufacturing and end of life of the aircraft are excluded from the analysis.

2.2 Fuel production

Renewable electricity either from wind or from photovoltaics is chosen as the main power source for all processes in the foreground. The production steps include water electrolysis,

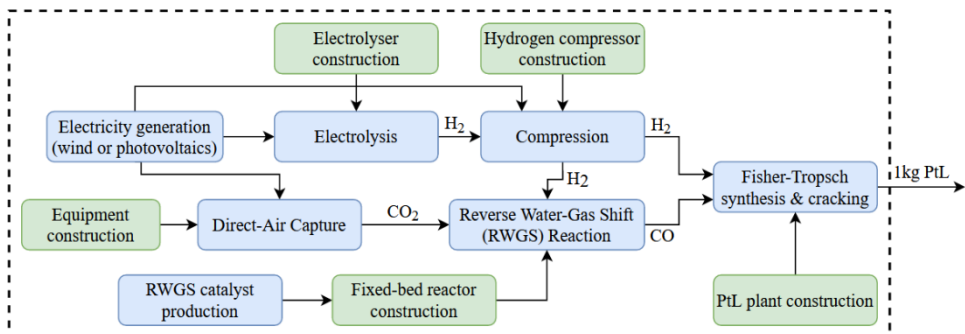


Fig. 1. Flow diagram of PtL production (own figure based on representation by [2]).

compression of the produced hydrogen and direct-air capture for the provision of carbon dioxide. These steps are followed by a reverse water-gas shift reaction and Fischer-Tropsch synthesis and cracking to produce the synthetic fuel. As shown in Fig. 1 the model also includes the construction of the required equipment which is shaded green. The life cycle inventory is based on [7]. For the reference case of fossil jet fuel, the processes describing the production of kerosene in Europe are used as implemented in the ecoinvent database.

2.3 From passenger demand to route network

In order to estimate the environmental impacts of flight operations, an operating scenario represented by a route network with flight frequencies is required. The methodology followed is depicted in Fig. 2. A global air-traffic forecast is calculated using a socioeconomic passenger demand forecast on airport-pair level and constraining the passenger and flight volumes by the respective airport capacities [8]. Based on this global forecast as well as aircraft design and performance data, the aircraft routes are assigned by considering factors such as the direct operating costs (DOCs) for airlines and schedule delay for passengers. This methodology provides an exemplary route network with flight frequencies for the considered aircraft design. The histogram in Fig. 2 shows the distribution of flights over different distances. The acquired route network serves as a basis for the environmental assessment.

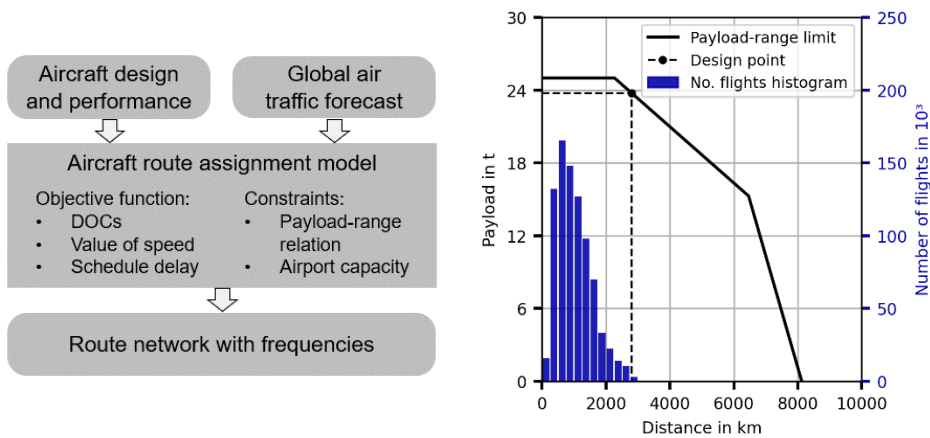


Fig. 2. Methodology for the traffic forecast of the fleet (left) and histogram of the number of flights per distance (right).

2.4 Fleet emissions and climate impact assessment

For the impact assessment especially of non-CO₂ emissions, not only the amount, but also the geographic position and altitude play an important role. For this purpose, the German Aerospace Center has developed a methodology, called GRIDLAB, that considers these parameters [9]. The climate impact of inflight emissions is assessed using the climate response model AirClim [10]. Fig. 3 shows the main steps of the methodology.

The central element of the methodology is the trajectory calculation module, which determines the 4-dimensional aircraft motion and the respective gaseous emissions based on the aerodynamic and engine characteristics of the aircraft. It considers the route network of the fleet as described in section 2.3 and simulates trajectories that respect the navigational constraints according to Air Traffic Management. Additionally, a flight profile optimisation for minimal fuel burn is conducted.

Subsequently the profile-based emissions are rasterised using a gridding algorithm. The resulting inventories are fed into the climate response model AirClim, which combines aircraft emissions with pre-calculated atmospheric data from simulations using a climate chemistry model. In addition to CO₂, also water vapor, the effect of nitrogen oxides on ozone and methane and the effect of contrail cirrus (CiC) are considered.

Different metrics can be chosen to assess the climate impact of the fleet operation. The Average Temperature Response (ATR) with a time horizon of 100 years is such a metric. It describes the mean near-surface temperature change over 100 years and enables a comparison of different technologies with respect to this temperature change. Another widely used metric is the Global Warming Potential (GWP) with a time horizon of 100 years. The climate change impact calculated following this methodology is combined with the impact from the production of the fuels as described in section 2.2 to derive the climate change impact during the entire lifecycle of the fleet.

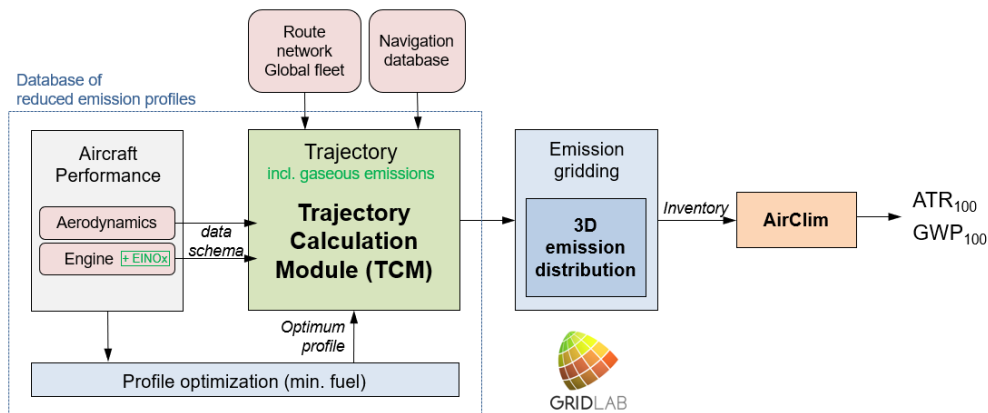


Fig. 3. Schematic representation of the methodology to estimate the emissions during flight and their climate impact.

3 Results and discussion

Using the methodology described above, the environmental impacts of the lifecycle of the aircraft fleet are calculated. The results of the impact category climate change are shown in Fig. 4. On the left, the GWP with a time horizon of 100 years in kilograms of CO₂ equivalents per passenger kilometre is shown for three different fuels: 1) the reference case of fossil fuel, 2) the PtL fuel produced using electricity from photovoltaic panels in Spain or 3) from wind turbines in the UK. These two locations are chosen as examples for European countries with good conditions for renewable energy production from solar or wind energy, respectively. The impacts during combustion of the fuel are dominant in all cases, with the impact for PtL fuels being significantly lower than that for fossil fuel for this life cycle phase, as expected. Looking at the production phase, PtL from wind energy has the lowest impact. All in all, the PtL fuel based on wind energy shows a potential to reduce the impact of up to 42% compared to the reference. Looking at the ATR of only the combustion (Fig. 4, right), the use of PtL leads to a similar reduction of 42% or approx. 0.15 mK for the fleet. This is mainly due to the neutralisation of the CO₂ impacts through direct air capture for the PtL production. The warming impact of the contrail induced cloudiness is also reduced due to the assumption of 62% less particle emission, while the impact of nitrogen oxides remains.

An assessment of more environmental impact categories included in the ILCD methodology for the production of the fuels reveals that for many of these categories, the synthetic fuel performs worse than the fossil reference (see Fig. 5). Of the selected impact categories,

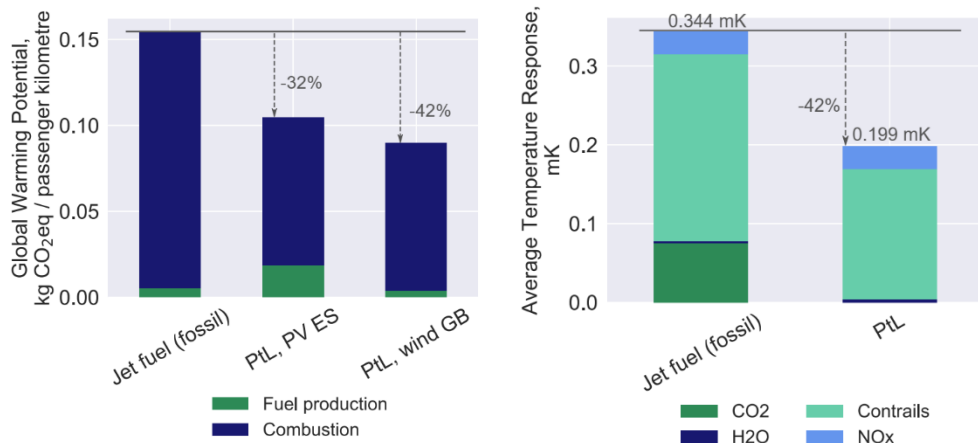


Fig. 4. GWP100 for the entire lifecycle of the fleet for the cases of fossil jet fuel, PtL from photovoltaic panels in Spain, and PtL from onshore wind turbines in the UK (left); ATR100 for the lifecycle of the fleet considering only the fleet operation for the cases of fossil jet fuel and PtL (right).

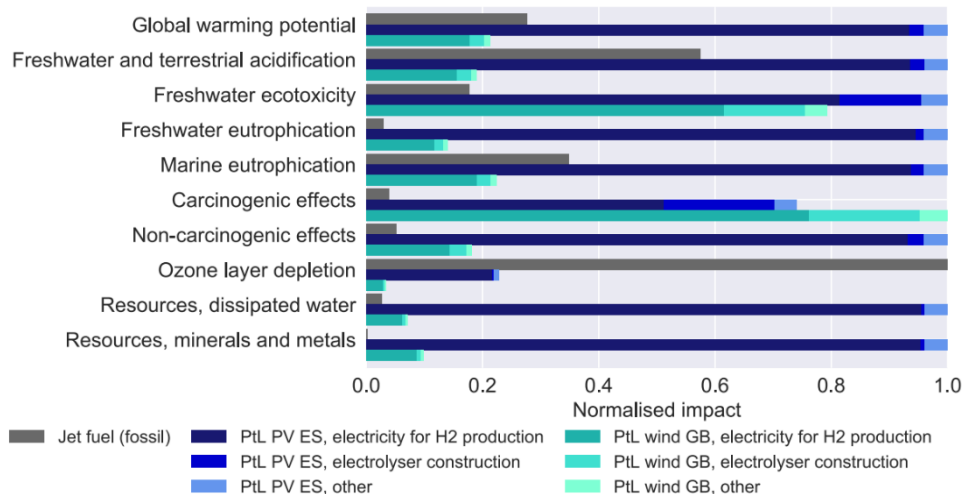


Fig. 5. Normalised environmental impacts of the production phase of fossil jet fuel, PtL from photovoltaic panels in Spain, and PtL from onshore wind turbines in the UK for selected ILCD impact categories, including a contribution analysis for the PtL production pathways.

only in the case of ozone layer depletion a significant improvement compared to the fossil reference can be observed for both cases of PtL. The high impact of fossil fuel in this category stems mainly from the Halon 1301 (Bromotrifluoromethane) that is included as an emission during petroleum production in the ecoinvent database; due to the phasing out of this substance, the actual impact is expected to be significantly lower. A contribution analysis of the two selected PtL pathways including processes with a relative impact higher than 5% in any of the categories shows that the electricity needed for the production of hydrogen via electrolysis has the highest impact in all categories (>80%), followed by the impacts from the electrolyser construction. The high impacts by the electricity for electrolysis come mainly from the provision of minerals and metals required for the manufacturing of renewable energy plants as well as the background electricity mix involved in the production of the plants. For instance, for the construction of photovoltaic panels, the comparatively high resource depletion of minerals and metals results mainly from the activities related to the

extraction of copper and its by-products such as tellurium. The high demand of water, especially in the case of photovoltaic energy based PtL, results mainly from the silicon production. The provision of metals (e.g. steel) for the electrolyser construction leads to its significant contribution in terms of ecotoxicity and carcinogenic effects. With increased efficiency of renewable energy technologies and improved end-of-life strategies, both the impact on water resources and that on minerals and metals might be improved in the future.

4 Conclusion

This case study demonstrated the potential of synthetic fuels from renewables to reduce climate impact of aviation based on the use case of a narrow-body aircraft fleet. Additionally, impact categories with higher burdens of PtL compared to fossil fuel were identified. The assessment methodology should be improved in terms of consistency between background and foreground systems by considering future developments of the energy sector and energy-intensive industry. Additionally, reuse and recycling options should be considered for the renewable electricity and fuel production technologies to further reduce their environmental impact. Newly introduced end-of-life policies, e.g. for photovoltaics, and ongoing research on the recovery and reuse of components or materials show promising signs in this direction. With regard to the impact assessment, an uncertainty analysis in relation to the processes included in the lifecycle inventories, but also related to the used indicators themselves should be conducted, in order to gain a better understanding of the results. In general, viewing the results from this comparison between fossil jet fuel and PtL, it can be concluded that a combination of different means will be needed to reduce the climate impact of aviation, not only technological such as new fuels or electrification but also operational such as climate-optimised flight trajectories.

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